

NEUTRINO PHYSICS*

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ABSTRACT

The theoretical motivations, experimental searches/hints, and implications of neutrino mass are surveyed.

1. Motivations

There are several motivations to search for possible non-zero neutrino masses.

- Fermion masses in general are one of the major mysteries/problems of the standard model. Observation or nonobservation of the (oddball) neutrino masses could introduce a useful new perspective on the subject.
- Nonzero ν masses are predicted in most extensions of the standard model. They therefore constitute a powerful probe of new physics.
- There may be a hot dark matter component to the universe. If so, neutrinos would be (one of) the most important things in the universe.
- The observed spectral distortion and deficit of solar neutrinos is most easily accounted for by the oscillations/conversions of a massive neutrino.
- The ratio of atmospheric ν_μ/ν_e may be suggestive of neutrino oscillations.
- With or without neutrino mass and oscillations, the solar neutrino flux is (with helioseismology) one of the two known probes of the solar core. A similar statement applies to Type-II supernovae.

Although there are strong motivations for neutrino mass and mixing from theory, cosmology, and astrophysics, the number of types of neutrinos is limited. The LEP lineshape measurements imply that there are only three ordinary light neutrinos, and big bang nucleosynthesis severely constrains the parameters of possible sterile neutrinos (which interact and are produced only by mixing). There are only a limited range of well-motivated possibilities for neutrino masses and mixings. The new generations of laboratory and solar neutrino experiments should be able to cover this range and either clearly establish non-zero masses (probably the first break with the standard model) or else falsify the interesting possibilities.

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2. Theory of Neutrino Mass

There are a confusing variety of models of neutrino mass. Here, I give a brief survey of the principle classes. For more detail, see ¹ and ².

Mass terms describe transitions between right (R) and left (L)-handed^a states. A Dirac mass term, which conserves lepton number, involves transitions between two different Weyl neutrinos^b, ν_L and N_R . That is, the right-handed state N_R is different from ν_R^c , the CPT partner of the ν_L . The form is

$$- \mathcal{L}_{\text{Dirac}} = m_D(\bar{\nu}_L N_R + \bar{N}_R \nu_L) = m_D \bar{\nu} \nu, \quad (1)$$

where the Dirac field is defined as $\nu \equiv \nu_L + N_R$. Thus a Dirac neutrino has four components ν_L , ν_R^c , N_R , N_L^c (the CPT partner of N_R), and the mass term allows a conserved lepton number $L = L_\nu + L_N$. This and other types of mass terms can easily be generalized to three or more families, in which case the masses become matrices. The charged current transitions then involve a leptonic mixing matrix (analogous to the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix), which can lead to neutrino oscillations between the light neutrinos.

For an ordinary Dirac neutrino the ν_L is active (*i.e.*, is in an SU_2 doublet) and the N_R is sterile^c (*i.e.*, is an SU_2 singlet, with no weak interactions except those due to mixing). The transition is $\Delta I = \frac{1}{2}$, where I is the weak isospin. The mass requires SU_2 breaking and is generated by a Yukawa coupling

$$- \mathcal{L}_{\text{Yukawa}} = h_\nu (\bar{\nu}_e \bar{e})_L \begin{pmatrix} \varphi^0 \\ \varphi^- \end{pmatrix} N_R + H.C. \quad (2)$$

One has $m_D = h_\nu v / \sqrt{2}$, where the vacuum expectation value (VEV) of the Higgs doublet is $v = \sqrt{2} \langle \varphi^0 \rangle = (\sqrt{2} G_F)^{-1/2} = 246$ GeV, and h_ν is the Yukawa coupling. A Dirac mass is just like the quark and charged lepton masses, but that leads to the question of why it is so small: one would require $h_{\nu_e} < 10^{-10}$ in order to have $m_{\nu_e} < 10$ eV.

A Majorana mass, which violates lepton number by two units ($\Delta L = \pm 2$), makes use of the right-handed antineutrino, $N_R = \nu_R^c$, rather than a separate Weyl neutrino. It is a transition from an antineutrino into a neutrino. Equivalently, it can be viewed as the creation or annihilation of two neutrinos, and if present it can therefore lead

^aThe subscripts L and R really refer to the left and right chiral projections. In the limit of zero mass these correspond to left and right helicity states.

^bA left (right)-handed particle is associated under CPT with a right (left)-handed antiparticle. The two together constitute a Weyl spinor.

^cSterile neutrinos are often referred to as “right-handed” neutrinos, but that terminology is confusing and inappropriate when Majorana masses are present.

to neutrinoless double beta decay. The form of a Majorana mass term is

$$- \mathbb{L}_{\text{Majorana}} = \frac{1}{2}m(\bar{\nu}_L\nu_R^c + \bar{\nu}_R^c\nu_L) = \frac{1}{2}m(\bar{\nu}_L C \bar{\nu}_L^T + H.C.) = \frac{1}{2}m\bar{\nu}\nu, \quad (3)$$

where $\nu = \nu_L + \nu_R^c$ is a self-conjugate two-component state satisfying $\nu = \nu^c = C\bar{\nu}^T$, where C is the charge conjugation matrix. If ν_L is active then $\Delta I = 1$ and m must be generated by either an elementary Higgs triplet or by an effective operator involving two Higgs doublets arranged to transform as a triplet.

For an elementary triplet $m \sim h_T v_T$, where h_T is a Yukawa coupling and v_T is the triplet VEV. The simplest implementation is the Gelmini-Roncadelli (GR) model³, in which lepton number is spontaneously broken by v_T . The original GR model is now excluded by the LEP data on the Z width. Variant models involving explicit lepton number violation or in which the Majoron (the Goldstone boson associated with lepton number violation) is mainly a weak singlet (*invisible* Majoron models) are still possible.

For an effective operator one expects $m \sim C v^2/M$, where C is a dimensionless constant and M is the scale of the new physics which generates the operator. The most familiar example is the seesaw model, to be discussed below.

It is also possible to consider mixed models in which both Majorana and Dirac mass terms are present. For two Weyl neutrinos one has a mass term

$$- L = \frac{1}{2} \left(\bar{\nu}_L \bar{N}_L^c \right) \begin{pmatrix} m_T & m_D \\ m_D & m_S \end{pmatrix} \begin{pmatrix} \nu_R^c \\ N_R \end{pmatrix} + H.C., \quad (4)$$

where $\nu_L \leftrightarrow \nu_R^c$ and $N_L^c \leftrightarrow N_R$ are the two Weyl states. m_T and m_S are Majorana masses which transform as weak triplets and singlets, respectively (assuming that the states are respectively active and sterile), while m_D is a Dirac mass term. Diagonalizing this 2×2 matrix one finds that the physical particle content is given by two Majorana mass eigenstates^d $n_i = n_{iL} + n_{iR}^c$, $i = 1, 2$.

An especially interesting case is the seesaw limit⁴, $m_T = 0$, $m_D \ll m_S$, in which there are two Majorana neutrinos

$$\begin{aligned} n_{1L} &\simeq \nu_L - \frac{m_D}{m_S} N_L^c \\ n_{2L} &\simeq \frac{m_D}{m_S} \nu_L + N_L^c \end{aligned} \quad (5)$$

with masses

$$\begin{aligned} m_1 &\sim \frac{m_D^2}{m_S} \ll m_D \\ m_2 &\sim m_S. \end{aligned} \quad (6)$$

^dIn the Dirac limit, $m_T = m_S = 0$, the two Majorana mass eigenstates, $\frac{1}{\sqrt{2}}(\nu_L \pm N_L^c)$ + CPT-partner, are degenerate and can be combined to form a Dirac neutrino.

Thus, there is one heavy neutrino and one neutrino much lighter than the typical Dirac scale. Such models are a popular and natural way of generating neutrino masses much smaller than the other fermion masses.

There are literally hundreds of versions of the seesaw and related models ². The heavy scale m_S can range anywhere from the TeV scale to the Planck scale. The TeV scale models are motivated, for example, by left-right symmetric models ⁵. Typically, the Dirac masses m_D are of the order of magnitude of the corresponding charged lepton masses, so that one expects masses of order 10^{-1} eV, 10 keV, and 1 MeV for the ν_e , ν_μ , and ν_τ , respectively. (The latter two violate cosmological bounds unless they decay rapidly and invisibly.) Intermediate scales, such as $10^{12} - 10^{16}$ GeV, are motivated by grand unification and typically yield masses in the range relevant to hot dark matter, and solar and atmospheric neutrino oscillations. The grand unified theories often imply Dirac masses $m_D \sim m_u$, where m_u is the mass of the up-type quark of the corresponding family. Depending on whether there is also a family hierarchy of heavy masses m_S , the light masses

$$m_{\nu_i} \sim C_i \frac{m_{u_i}^2}{m_{S_i}}, \quad (7)$$

of the i^{th} family may vary approximately quadratically with m_{u_i} (the quadratic seesaw) or linearly (the linear seesaw) ⁶. $C_i \sim (0.05 - 0.4)$ in (7) is a radiative correction. Typical light neutrino masses in the quadratic seesaw are (10^{-7} eV, 10^{-3} eV, 10 eV) for $M_{S_i} \sim 10^{12}$ GeV (the intermediate seesaw, expected in some superstring models or in grand unified theories with multiple breaking stages). Such masses would correspond to $\nu_e \rightarrow \nu_\mu$ in the Sun, and ν_τ a dark matter candidate (or, for a somewhat smaller ν_τ mass, $\nu_\mu \rightarrow \nu_\tau$ atmospheric neutrino oscillations). Similarly, for $M_{S_i} \sim 10^{16}$ GeV (the grand unified seesaw, expected in old-fashioned grand unified theories with large Higgs representations) one typically finds smaller masses around (10^{-11} eV, 10^{-7} , 10^{-2} eV), suggesting $\nu_e \rightarrow \nu_\tau$ in the Sun. In such models one often (but not always) finds that the lepton and quark mixing matrices are similar.

A very different class of models are those in which the neutrino masses are zero at the tree level (typically because no Weyl singlets or elementary Higgs triplets are introduced), but only generated by loops ⁷, *i.e.*, radiative generation. Such models are very attractive in principle and explain the smallness of m_ν . However, the actual implementation generally requires the *ad hoc* introduction of new Higgs particles with nonstandard electroweak quantum numbers and lepton number-violating couplings.

3. Laboratory Limits

There is no compelling laboratory evidence for non-zero neutrino mass. The direct limits from kinematic searches for the masses yield the upper limits ⁸

$$m_{\nu_e} < 5.1 \text{ eV, tritium } \beta \text{ decay}$$

$$\begin{aligned}
m_{\nu_\mu} &< 160 \text{ keV}, \pi \rightarrow \mu\nu_\mu \\
m_{\nu_\tau} &< 31 \text{ MeV}, \tau \rightarrow \nu_\tau + n\pi.
\end{aligned}
\tag{8}$$

There is also a preliminary new upper limit $m_{\nu_\tau} < 24 \text{ MeV}$ from ALEPH ⁹. All of these are much smaller than the corresponding charged lepton masses. One disturbing feature is that the tritium β decay experiments all yield negative m^2 values, with a weighted average $m_{\nu_e}^2 = (-96 \pm 21) \text{ eV}^2$, suggesting a common systematic or theoretical uncertainty in the experiments. Until this is understood the precise upper limit must be considered somewhat questionable.

Searches for neutrinoless double beta decay ($\beta\beta_{0\nu}$) are sensitive to the combination of Majorana masses^e $\langle m_{\nu_e} \rangle = \sum_i \eta_i U_{ei}^2 m_i$, where it is assumed that the ν_e is a superposition $|\nu_e\rangle = \sum_i U_{ei} |\nu_i\rangle$ of mass eigenstates. η_i is a CP phase, allowing for cancellations between the different terms, as occurs for a Dirac neutrino. Currently, the most stringent upper limit is $\langle m_{\nu_e} \rangle < 0.68 \text{ eV}$ from the Heidelberg-Moscow ⁷⁶Ge experiment ¹⁰. There is some uncertainty in the precise value of the upper limit, since it depends on a theoretical calculation of a nuclear matrix element.

There have been many accelerator and reactor searches for neutrino oscillations. None have reported a compelling positive signal. However, the Los Alamos LSND experiment has recently reported (in the popular press) indications of possible $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations. If confirmed, values $|\Delta m^2| = O(5 \text{ eV}^2)$ for the mass-squared difference $\Delta m^2 = m_2^2 - m_1^2$ would be required.

4. Solar Neutrinos

There are currently four solar neutrino experiments ¹¹. The Kamiokande water Cerenkov experiment ¹² can observe only the highest energy ⁸B neutrinos. The Homestake ¹³ radiochemical chlorine experiment also has its largest sensitivity at the highest energies, but has some sensitivity to the lower energy parts of the ⁸B spectrum and to the higher ⁷Be line. The two radiochemical gallium experiments, SAGE ¹⁴ and GALLEX ¹⁵, are sensitive to the low energy pp neutrinos, as well as to the higher energy neutrinos. The GALLEX experiment has recently demonstrated its detection efficiency using an intense ⁵⁰Cr source, for which they observed 1.04 ± 0.12 times the expected numbers of counts ¹⁶.

The results of the experiments are compared with the predictions of two standard solar models ¹⁷, that of Bahcall and Pinsonneault (BP) ¹⁸ and that of Turck-Chieze and Lopes (TCL) ¹⁹, in Table 1. It is seen that all of the observed rates are well below the theoretical predictions.

The solar neutrino problem has two aspects. The older and less significant is that all of the experiments are below the SSM predictions. This was never a serious concern for the Kamiokande and Homestake experiments individually, which are mainly

^eThis is an approximation valid if all of the $m_i \ll 1 \text{ MeV}$.

Exp	BP SSM	TCL SSM	Exp	Exp/BP	Exp/TCL
Kamiokande	5.69 ± 0.82	4.4 ± 1.1	$2.89^{+0.22}_{-0.21} \pm 0.35$	$0.50 \pm 0.07[0.07]$	$0.65 \pm 0.09[0.16]$
Homestake	8 ± 1	6.4 ± 1.4	$2.55 \pm 0.17 \pm 0.18$	$0.32 \pm 0.03[0.04]$	$0.40 \pm 0.04[0.09]$
Gallium (combined)	131.5^{+7}_{-6}	122.5 ± 7	77 ± 9	$0.59 \pm 0.07[0.03]$	$0.63 \pm 0.07[0.04]$
SAGE			74^{+13+5}_{-12-7}		
GALLEX			$79 \pm 10 \pm 6$		

Table 1: Predictions of the BP and TCL standard solar models for the Kamiokande, Homestake, and Gallium experiments compared with the experimental rates. The Kamiokande flux is in units of $10^6/cm^2 s$, while the Homestake and gallium rates are in SNU (10^{-36} interactions per atom per s). The experimental rates relative to the theoretical predictions are shown in the last two columns, where the first uncertainty is experimental and the second is theoretical. All uncertainties are 1σ .

sensitive to the high energy 8B neutrinos, which are the least reliably predicted. However, the predictions for the gallium experiments are harder to modify due to the constraint of the solar luminosity, and the statistics on the gallium experiments are now good enough that the deficit observed there is hard to account for.

A second and more serious problem is that the Kamiokande rate indicates less suppression than the Homestake rate. The Homestake experiment has a lower energy threshold, and the lower observed rate suggests that there is more suppression in the middle of the spectrum (the 7Be line and the lower energy part of the 8B spectrum) than at higher energies^{20,26}. This is very hard to account for by astrophysical or nuclear physics mechanisms: the 8B is made from 7Be so any suppression of 7Be should be accompanied by at least as much suppression of 8B . Furthermore, all known mechanisms for distorting the 8B β decay spectrum are negligible²⁷.

4.1. Astrophysical Solutions

Unless the experiments are seriously in error, there must be some problem with either our understanding of the sun or of neutrinos. Clearly, the standard solar models (SSM) cannot account for the data, but there is the possibility of a highly nonstandard solar model (NSSM). For example, some of the astrophysical parameters or nuclear cross sections could differ significantly from what is usually assumed, or there could be some new physics ingredient, such as a large magnetic field in the core, that is not included in the standard calculations.

Most of the NSSM manifest themselves for the neutrinos by leading to a lower temperature for the core of the sun^{28,29}. However, in all reasonable models the 8B neutrinos should be the most temperature sensitive, leading to the lowest counting rate (relative to the SSM) for the Kamiokande experiment, contrary to observations. Similarly, a lower cross section for 7Be production would suppress the 7Be and 8B equally. A lower cross section for 8B production, which has been suggested by

one recent experiment ³⁰, would actually make matters worse: by accounting for the suppression of the ⁸B neutrinos, there would be less room for other mechanisms to explain the larger ⁷Be suppression. None of these mechanisms explain the data ³¹.

Though most explicitly-constructed nonstandard models involve either the temperature or the cross sections ²⁹ there is always the possibility of very nonstandard physical inputs which cannot be described in this way. It is therefore useful to carry out a model-independent analysis ^{21,22,32}. All that matters for the neutrinos are the magnitudes $\phi(pp)$, $\phi(Be)$, $\phi(B)$ and $\phi(CNO)$ of the flux components. We can analyze the data making only three minimal assumptions. One is that the solar luminosity is quasi-static and generated by the normal nuclear fusion reactions. This implies

$$\phi(pp) + \phi(pep) + 0.958\phi(Be) + 0.955\phi(CNO) = 6.57 \times 10^{10} \text{cm}^{-2} \text{s}^{-1}, \quad (9)$$

where the coefficients correct for the neutrino energies. The second assumption is that astrophysical mechanisms cannot distort the shape of the ⁸B spectrum significantly from what is given by normal weak interactions. (All known distortion mechanisms are negligibly small ²⁷.) It is this assumption which differentiates astrophysical mechanisms from MSW, which can distort the shape significantly. Our third assumption is that the experiments are correct, as are the detector cross section calculations.

In this (almost) most general possible solar model all one has to play with are the four neutrino flux components^f subject to the luminosity constraint. The strategy is to fit the data to the ⁷Be and ⁸B fluxes. For each set of fluxes, one varies $\phi(pp)$ and $\phi(CNO)$ so as to get the best fit. The CNO and other minor fluxes play little role because they are bounded below by zero, and larger values make the fits worse. Figure 1 displays the allowed region from all data, updated from ^{21,22}. The best fit would occur in the unphysical region of negative ⁷Be fluxes. Constraining the flux to be positive, the best fit requires $\phi(^7\text{Be}) < 7\%$ and $\phi(^8\text{B}) = 41 \pm 4\%$ of the SSM ^{21,22}. This, however, has a poor χ^2 of 3.3 for 1 d.f., which is excluded at 93% CL.

More important, the best fit is in a region that is hard to account for by astrophysical mechanisms. Figure 1 also displays predictions of the BP and TCL standard solar models, the 1,000 Monte Carlos SSMs of Bahcall and Ulrich (dots) ³³, other explicitly constructed nonstandard models ¹¹, and the general predictions of cool sun and low cross section models. All are far from the allowed region. Similar conclusions hold even if one ignores any one of the classes of experiment ^{22,23,25,34}, as shown in Table 2. It is unlikely that any NSSM will explain the data.

4.2. The MSW Solution

A second possibility is particle physics solutions, which invoke nonstandard neutrino properties. Of these I will concentrate on what I consider the simplest and most favored explanation, the Mikheyev-Smirnov-Wolfenstein (MSW) matter enhanced

^fThe uncertainties associated with $\phi(pep)$ are negligible.

Figure 1: 90% CL combined fit for the ${}^7\text{Be}$ and ${}^8\text{B}$ fluxes. Also shown are the predictions of the BP and TCL SSM's, 1000 Monte Carlo SSM's ³³, various nonstandard solar models, and the models characterized by a low core temperature or low cross section for ${}^8\text{B}$ production. Updated from ^{21,22,35}.

	pp	${}^7\text{Be}$	${}^8\text{B}$	CNO
Without MSW:				
Kam + Cl + Ga	$1.089 - 1.095$	< 0.07	0.41 ± 0.04	< 0.26
Kam + Cl	$1.084 - 1.095$	< 0.13	0.42 ± 0.04	< 0.38
Kam + Ga	$1.085 - 1.095$	< 0.13	0.50 ± 0.07	< 0.56
Cl + Ga	$1.082 - 1.095$	< 0.16	0.38 ± 0.05	< 0.72
With MSW:				
Kam + Cl + Ga	< 1.095	–	1.15 ± 0.53	–

Table 2: Fluxes compared to the BP standard solar model for various combinations of experiments. From ^{21,22,35}.

Figure 2: Allowed regions at 95% CL from individual experiments and from the global MSW fit. The Earth effect is included for both time-averaged and day/night asymmetry data, full astrophysical and nuclear physics uncertainties and their correlations are accounted for, and a joint statistical analysis is carried out. The region excluded by the Kamiokande absence of the day/night effect is also indicated. From ^{37,35}.

conversion of one neutrino flavor into another ³⁶. There are other possible explanations ¹¹, such as the more complicated 3-flavor MSW, vacuum oscillations, neutrino decay, large magnetic moments, or violation of the equivalence principle. Many of these are disfavored by the data and are, to my mind, less natural.

There are now a number of analyses of the data assuming MSW ^{37,45,11}. One usually assumes the SSM predictions for the initial neutrino fluxes. It is important to properly incorporate their theoretical uncertainties, which can be due to the core temperature T_C , as well as to the production and detector cross sections. One must also include the correlations of those uncertainties between different flux components and between different experiments ³⁷, and carry out a joint χ^2 analysis of the data to find the allowed regions.

The Earth effect ⁴⁶, *i.e.*, the regeneration of ν_e in the Earth at night, is significant for a small but important region of the MSW parameters, and not only affects the time-average rate but can lead to day/night asymmetries. The Kamiokande group has looked for such asymmetries and has not observed them ⁴⁷, therefore excluding a particular region of the MSW parameters in a way independent of astrophysical uncertainties.

The allowed regions from the overall fit for normal oscillations $\nu_e \rightarrow \nu_\mu$ or ν_τ are shown in Figure 2, assuming the BP SSM for the initial fluxes. There are two solutions at 95% C.L., one for small mixing angles (non-adiabatic), and one for large angles. The former gives a much better fit. There is a second large angle solution with smaller Δm^2 , which only occurs at 99% C.L. MSW fits can also be performed using other solar models as inputs ^{37,35}. The allowed regions are qualitatively similar, but differ in detail. One can even go a step further and consider nonstandard solar models and MSW simultaneously ^{22,37}. There is now sufficient data to determine both

the MSW parameters and the core temperature in a simultaneous fit. One obtains $T_C = 1.00 \pm 0.03$, in remarkable agreement with the standard solar model prediction 1 ± 0.006 . One can similarly allow the 8B flux to be a free parameter^{22,37}.

One can also consider transitions $\nu_e \rightarrow \nu_s$ into sterile neutrinos. These are different in part because the MSW formulas contain a small contribution from the neutral current scattering from neutrons. Much more important is the lack of the neutral current scattering of the ν_s in the Kamiokande experiment. There is a non-adiabatic solution similar to the one for active neutrinos, though the fit is poorer. However, there is no acceptable large angle solution because of the lack of a neutral current, which makes that case similar to astrophysical solutions. Oscillations into a sterile neutrino in that region are also disfavored by Big Bang nucleosynthesis¹¹.

The next generation of solar neutrino experiments, SNO, Superkamiokande, and Borexino, should be able to cleanly establish or refute the MSW and other particle physics and astrophysical interpretations of the solar neutrino anomaly¹. They will have at their disposal a number of observables that are relatively free of astrophysical uncertainties, including neutral to charged current ratios, spectral distortions, and day-night and seasonal time dependence. If MSW does turn out to be correct, there should be enough data to simultaneously determine the neutrino mass and mixing parameters and the initial neutrino flux components²².

5. Atmospheric Neutrinos

Atmospheric neutrinos, which are the decay products of hadrons produced by cosmic ray interactions in the atmosphere, have been detected in a number of underground experiments. Although the predictions for individual flux components, *i.e.*, ϕ_{ν_e} and ϕ_{ν_μ} , are uncertain by at least 20%⁴⁸, the ratio $r = \phi_{\nu_\mu}/\phi_{\nu_e}$ is much cleaner, with various calculations agreeing at the 5% level.

The Kamiokande and IMB experiments⁴⁹ have both observed a statistically significant deviation of r from the expected value, as indicated in Table 3. The value quoted is determined from the ratio of muons to electrons produced within the detector, compared to the theoretical expectation. The Soudan II data is consistent, though with larger statistical errors. Earlier results from Frejus and NUSEX do not show signs of a deviation, but again have large statistical uncertainties.

The small value of r observed by Kamiokande and IMB suggests the possibility of the disappearance of ν_μ or the appearance of extra ν_e . In particular, the results could be accounted for by $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_e$ oscillations⁹ with $\Delta m^2 \sim 10^{-2} \text{ eV}^2$ and near maximal mixing ($\sin^2 2\theta > 0.5$). The oscillation interpretation has recently been supported by the observation by Kamiokande of an anomaly in r for multi-GeV events⁵⁰, which is consistent with their earlier sub-GeV sample (and which, incidentally, excludes the interesting possibility of a positron excess due to proton decay⁵¹,

⁹Oscillations into sterile neutrinos are strongly disfavored by nucleosynthesis constraints¹¹.

Experiment	value
Kamiokande (multi-GeV)	$0.57^{+0.08}_{-0.07} \pm 0.07$
Kamiokande (sub-GeV)	$0.60^{+0.06}_{-0.05} \pm 0.05$
IMB	$0.54 \pm 0.05 \pm 0.12$
Soudan II	$0.69 \pm 0.19 \pm 0.09$

Table 3: Ratios $R \equiv r_{\text{data}}/r_{\text{theory}}$ observed by recent experiments. The first (second) uncertainty is statistical (systematic).

$p \rightarrow e^+ \nu \bar{\nu}$). Also, the multi-GeV data exhibit a zenith angle distribution which is suggestive of oscillations, though the statistics are not compelling. However, there are caveats. In particular, (a) the anomaly has not been observed by all groups. (b) There are possible uncertainties due to the interaction cross sections in the detector and particle identification. However, at the energies involved it is unlikely that there would be significant differences between the ν_μ and ν_e cross sections, and the preliminary results from a KEK beam test do not show any signs of particle misidentification for Kamiokande. (c) The IMB collaboration has also analyzed the ratio of throughgoing to stopping muons. No anomaly is observed, excluding the lower part of the Δm^2 range, e.g., $\sim 10^{-3} \text{ eV}^2$, suggested by r . (d) IMB has also measured the absolute flux of upward muons. No anomaly was observed, nominally excluding the interesting parameter range. However, this conclusion relies on the theoretical calculation of the absolute ν_μ flux, and also involves uncertainties from the deep inelastic scattering cross section⁴⁸.

One can regard the atmospheric neutrino anomaly as a strong suggestion for neutrino oscillations. However, confirmation will probably require long baseline oscillation experiments, which are sensitive to small Δm^2 and large mixings. Experiments sensitive to ν_μ oscillations are proposed or suggested for Brookhaven, Fermilab, CERN, and KEK. There are also several proposals for long baseline experiments at reactors, which, however, are only sensitive to $\bar{\nu}_e$ disappearance.

6. Cosmological Neutrinos

The combination of COBE data⁵² and the distribution of galaxies on large and small scales is hard to understand on the basis of simple cold dark matter. One possibility is that in addition to cold dark matter there is a small admixture⁵³ of hot dark matter, presumably due to a massive τ neutrino with a mass in the range $m_{\nu_\tau} \sim (1 - 35) \text{ eV}$ ⁵⁴. Even better fits are obtained if there are two nearly degenerate neutrinos in the few eV range⁵⁵, and speculations on these lines have been encouraged by the possible LSND observation of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. There are, however, alternative explanations⁵⁶, such as a 100 eV sterile neutrino, decaying MeV neutrino, cosmological constant, topological defects, low density universe, or a tilted initial spectrum.

If the ν_τ has a mass in the eV range then, unless its mixing with ν_μ is extremely small, $\nu_\mu \rightarrow \nu_\tau$ oscillations should be observable in the CHORUS and NOMAD experiments at CERN, and the later E803 at Fermilab, all of which will be sensitive to ν_τ appearance for very small $\sin^2 2\theta$ for Δm^2 in the eV² range.

7. Implications

As described in Section 2 many theories with coupling constant unification, such as grand unified theories, predict a seesaw-type mass ^{4,6}

$$m_{\nu_i} \sim \frac{C_i m_{u_i}^2}{M_N}, \quad (10)$$

where M_N is the mass of a superheavy neutrino, $u_i = u, c, t$ are the up-type quarks, and C_i is a radiative correction. The general Δm^2 range suggested by the solar neutrinos is consistent with the GUT-seesaw range. In particular, in the string motivated models one expects the heavy mass to be a few orders of magnitude below the unification scale ⁵⁷. As an example, for $M_N \sim 10^{-4} M_{GUT} \sim 10^{12}$ GeV one predicts

$$\begin{aligned} m_{\nu_e} &< 10^{-7} \text{ eV} \\ m_{\nu_\mu} &\sim 10^{-3} \text{ eV} \\ m_{\nu_\tau} &\sim (3 - 20) \text{ eV}. \end{aligned} \quad (11)$$

In this case one would expect MSW oscillations of $\nu_e \rightarrow \nu_\mu$ in the sun, and perhaps the ν_τ is in the range relevant to hot dark matter. If this is the case there is a good chance that $\nu_\mu \rightarrow \nu_\tau$ oscillations will be observed in accelerator appearance experiments now underway at CERN. Alternately, for small modifications in the seesaw one could have somewhat smaller ν_τ masses that could lead to $\nu_\mu \rightarrow \nu_\tau$ oscillations in the range relevant to the atmospheric neutrino anomaly.

The specific predictions are highly model dependent, and one cannot make anything more than general statements at this time. It will be important to follow up all experimental possibilities. If oscillations are responsible for the atmospheric neutrino results it should be possible to prove it with long baseline oscillation experiments proposed at Fermilab, Brookhaven, and elsewhere.

It is difficult to account for solar neutrinos, a component of hot dark matter, and atmospheric neutrinos simultaneously. There are just not enough neutrinos to go around. Confirmation of the LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ events would further complicate the situation. Attempts to account for all of these effects must invoke additional sterile neutrinos and/or nearly degenerate neutrinos, so that the mass differences can be much smaller than the average masses ⁵⁸.

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